2 The effect of climate on lake mixing patterns and temperatures

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INTRODUCTION

The maritime geographical location has been said to give distinctive characteristics of water mixing to lakes (Hutchinson 1957, pp. 443-444), but such effects have never been described in detail. New Zealand's lakes should exemplify well these maritime distinctions, and in this chapter features of water column mixing and temperature changes are identified which can distinguish New Zealand lakes from those elsewhere.

Surface wind provides the main external force in this respect to mix the water column, but heating of surface waters by solar radiation introduces a vertical gradient of water density that stabilises the column. The balance between these two variables determines the distribution of kinetic energy and so the vertical extent of turbulence. Mixing events are recorded in the temperature profiles, which traditionally in limnology have given important, but largely visual, information about the annual patterns of lake mixing. More recently however, temperature profiles have been used analytically to differentiate regional characteristics of lakes (e.g., Straskraba 1980) and to quantify the periodicity of mixing events in different parts of the lake (e.g., Imberger 1985a; 1985b); approaches which will be utilised here.

Temperature profiles, by themselves, do not reveal details of how the mixing process is actually brought about within the lake. These are phenomena difficult to measure, and in New Zealand have hardly been investigated as yet. For our purpose of distinguishing regional features we therefore have to rely upon comparisons of the temperature profiles against lake size and location, and against climate, particularly the wind regime.

It has previously been suggested (Jolly & Irwin 1975; Stout 1975) that New Zealand lakes have lower amplitudes of annual temperature change and deeper mixed epilimnia than might be expected by comparison with lakes in similar latitudes (c. 35° – 47° N) in the Northern Hemisphere, and that these features were effects of the maritime location. The suggestions were based on rather limited information and no description of the relative importance of individual climatic factors was offered. However, much more data are available though thinly scattered in the literature, and have been compiled here to permit simple correlations of field observations with major climatic features. Two aspects of climate are used; the annual cycle of air temperature, and the pattern of wind strength. We are also concerned to describe temperature conditions, in terms of average maxima and minima and annual ranges, as background to the metabolic environment to be found in New Zealand lakes.

Table 1 Temperature data sources for New Zealand lakes.

North Island lakes	Complete annual data	Occasional or seasonally incomplete data
Araoatotamahine	Bayly 1962	
Atiamuri		Irwin & Heath 1972
Auckland temporary pond	Barclay 1966	
Auxiliary Nihotupu Reservoir	Green 1974	
Ngahewa		McColl & Forsyth 1975
Ngapouri	Jolly 1959, 1968, Fish 1969, 1970	Irwin 1968, McColl 1972
Ohakuri	Coulter et al. 1983	Irwin & Health 1972
Okareka	Jolly 1959, 1968	Irwin 1968, McColl 1972
Okaro	Jolly 1959, 1968, Fish 1969, 1970	Irwin 1968, McColl 1972
Okataina	Jolly 1959, 1968	Irwin 1968, McColl 1972
Ototoa	Green 1975	
Parkinson's	Mitchell et al. 1984	
Pukepuke Lagoon	Gibbs 1973	
Pupuke	Barker 1970	
Rerewhakaaitu	Jolly 1959, 1968, Chapman et al. 1981	
Rotoehu	Jolly 1959, 1968, Fish 1969, 1970	Irwin 1968, McColl 1972
Rotoiti	Jolly 1959, 1968, Fish 1969, 1975	Irwin1968
Rotokakahi	Jolly 1959, 1968	Irwin 1968, McColl 1972
Rotokare		Taranaki Catchment Commission 1980
Rotokawa		Forsyth 1977
Rotoma	Jolly 1959, 1968	Irwin 1968, McColl 1972
Rotomahana	Jolly 1959, 1968	Irwin 1968
Rotongaio	Jolly 1959, 1968, Viner 1984	
Rotorua	Jolly 1959, 1968, Fish 1969, 1970, 1975	Irwin 1968, Burnett & Davis 1980
Rotowhero		McColl & Forsyth 1973
Tarawera	Jolly 1959, 1968	Irwin 1968
Taupo	Jolly 1959, 1968	
Tikitapu	Jolly 1959, 1968	Irwin 1968, McColl 1972
Waikaremoana	Jolly 1959, 1968	
Waikareiti	Jolly 1959, 1968	
West Coast sand dune lakes		Cunningham 1953

South Island lakes	Complete annual data	Occasional or seasonally incomplete data
Acland	Stout 1969	
Brunner		Paerl et al. 1979
Evelyn	Stout 1969	
Grasmere	Stout 1969, 1984	
Georgina	Stout 1969	
Handon	Stout 1969	
Haupiri		Paerl et al. 1979
Hayes	Mitchell & Burns 1979	
Henrietta	Stout 1969	
Hochstetter	Stout 1969	
Howard	Stout 1969	
Ida	Stout 1969	
Johnson	Mitchell & Burns 1979	
Kangaroo		Paerl et al. 1979
Kaniere		Paerl et al. 1979
Lady		Paerl et al. 1979
Lyndon	Stout 1969	
Mahinerangi	Mitchell 1971	
Manapouri		Irwin 1971
Marymere	Stout 1969	
Mudgie		Paerl et al. 1979
Pearson	Stout 1969, 1984	

South Island lakes	Complete annual data	Occasional or seasonally incomplete data
Poerua		Paerl et al. 1979
Rotoiti S.I.		Irwin 1978
Rotoroa		Irwin 1978
Roundabout	Stout 1969	
Saddle Hill pond	Byars 1960	
Sarah	Stout 1969	
Selfe	Stout 1969	
Tekapo		Irwin & Pickrill 1982
Tomahawk Lagoon	Mitchell 1971	
Tripp	Stout 1969	
Waipori	Mitchell 1971	
Wakatipu		Jolly 1959, Irwin & Jolly 1970, Pickrill & Irwin 1982

The sources for the temperature data are listed in Table 1. North Island lakes are probably the best known and seasonal temperature records have been published for various lakes in the Rotorua and Taupo areas, but less detailed information exists on a wide variety of other lakes. For the South Island the smaller lakes in the high country have been most studied, but occasional (usually summer) measurements have been made on other waters. There is very little published data from the larger glacial lakes. Jolly (1959) visited a number of them and although she did not obtain any complete seasonal records, Irwin & Jolly (1970) and Pickrill & Irwin (1982) combined her data from Lake Wakatipu with other isolated records to obtain a composite seasonal record for this lake. From a comparative point of view, the early work of Jolly (1959) is still the most inclusive and valuable. The only previous attempt to summarise general features of New Zealand lake temperatures is that of Jolly & Irwin (1975).

The arrangement of this account is to outline the climatic environment of the seasonal cycles of wind and solar irradiance. Against this is set a general description of lake mixing patterns, and then a more detailed regional comparison of temperature changes and the potential for lakes to mix.

SYNOPSIS OF THE CLIMATE

New Zealand's climate has been described in detail by Garnier (1958), Maunder (1970) and Tomlinson (1975). A useful account from an ecological viewpoint is that of Coulter (1973), and other aspects can be found in chapters 4 and 16.

Factors determining the climate are the country's position in the midst of a vast ocean and within the mid-latitude belt of westerly winds, its shape and topography. The climate is milder and less subject to extremes than in continental areas, and is moist, windy, and with low annual cloudiness. The weather is changeable as a result of regular successions of eastward moving anticyclones and depressions, and their associated cold fronts, which pass over the country at approximately 5 – 10 day intervals.

The mean annual temperature range is small, summer temperatures are relatively cool and winter conditions generally mild (Fig. 1A). Temperatures decrease steadily from north to south, but there are also considerable differences between inland areas of both islands. The lowest winter temperatures occur in southern central South Island and the central plateau of the North Island, areas which are either cut off from oceanic influences by the ranges to the west, or at relatively high altitudes (Figs. 1B, 1C). The greatest annual ranges (c.14 °C) are found in areas of central Otago, while in North Auckland, the west coast of both islands, and about Wellington the values are less than 9 °C.

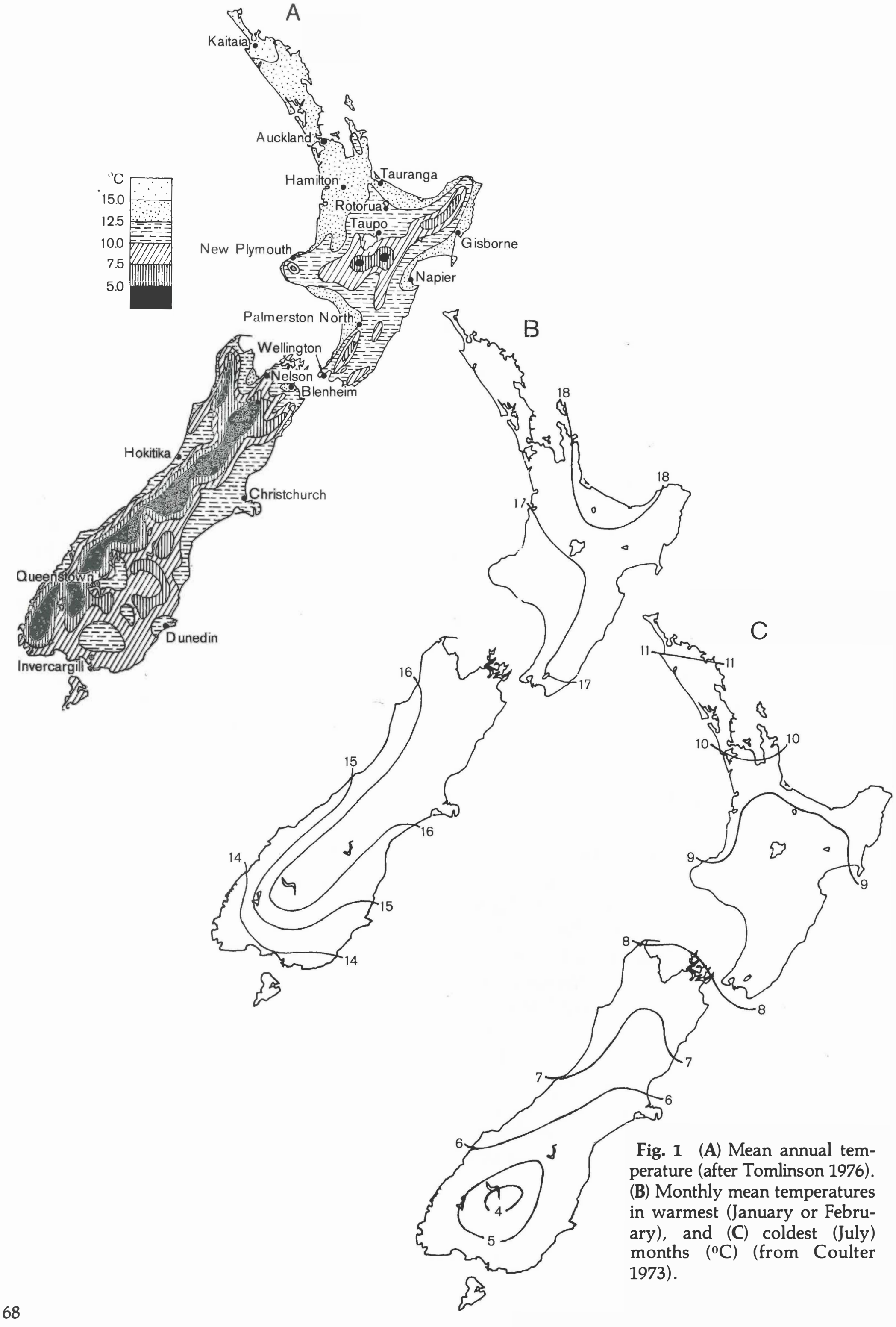


Fig. 1 (**A**) Mean annual temperature (after Tomlinson 1976). (**B**) Monthly mean temperatures in warmest (January or February), and (**C**) coldest (July) months (°C) (from Coulter 1973).

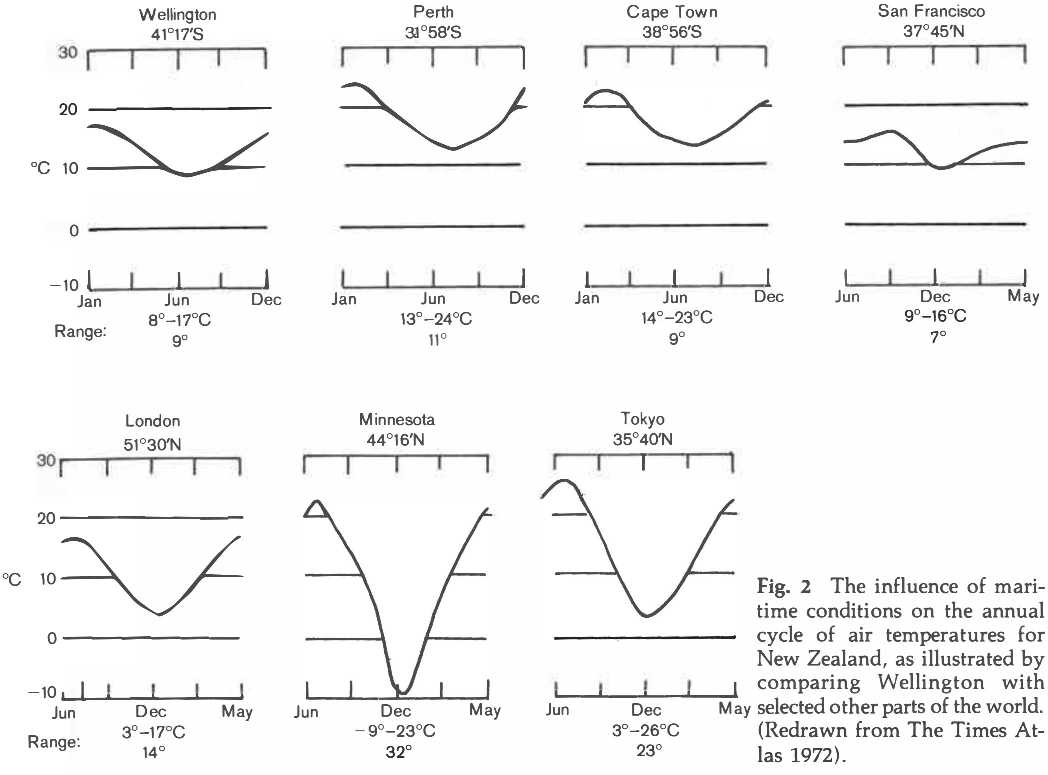


Fig. 2 The influence of maritime conditions on the annual cycle of air temperatures for New Zealand, as illustrated by comparing Wellington with selected other parts of the world. (Redrawn from The Times Atlas 1972).

Figure 2 compares the annual air temperature regime in New Zealand with other places. Wellington is used as a conveniently central reference location. The temperature range is similar to other Southern Hemisphere west coast maritime locations such as Perth and Cape Town, but these places have overall higher temperatures, and will have correspondingly warmer waters. At a dam near Perth surface temperature has been known to reach 35 °C. The highest surface temperature for a New Zealand lake known to the present authors is 31.5 °C (Lake Maratoto, January 1980). Unfortunately neither the west coast of South Africa nor of Australia have many natural lakes that can usefully be compared to those in New Zealand. Presumably the coast of southern Chile would have the most similar climate to New Zealand's but there are no limnological data for the many Chilean lakes for comparisons to be made. In the Northern Hemisphere, the coastal climate of California has temperature conditions similar to those in New Zealand, but most of the Californian lakes which are deep enough for comparisons are at high altitude. London, used here as representative of a northern maritime climate, and also not far from the site of the many limnological studies of the English Lake District, has a similar annual maximum temperature to Wellington but a much lower minimum, allowing for dimictic lakes to be more frequent, in contrast to New Zealand waters (see below). Both Minnesota and Tokyo are included in Fig. 2 as representatives of the continental, typically large, temperature range at analogous latitudes to New Zealand, and also because these places are near locations of many lakes (Lake Biwa, Japan, is mentioned below). It is evident that the combination in New Zealand of the reduced temperature range of a cool maritime climate with an abundance of lakes, and substantial limnological records, is very unusual.

Westerly winds predominate throughout the year although there may be considerable modification by local topography. In many North Island areas southwesterly flows predominate. Average wind speeds are high. To facilitate comparison with published information from other countries the wind energy flux has to be used (wind energy flux = WEF = $\frac{1}{2} pv^3$, where p is the air density and **v** the wind velocity). By comparison with, in particular, the USA, areas of Canada and the USSR, average wind energy fluxes in New Zealand have been classified as high to very high (Cherry 1976). The country-wide average wind speed is 4.9 $m.s^{-1}$, but could be higher because particularly windy locations are not measured (Cherry 1976). There are considerable diurnal and seasonal variations in wind speed (Fig. 3).

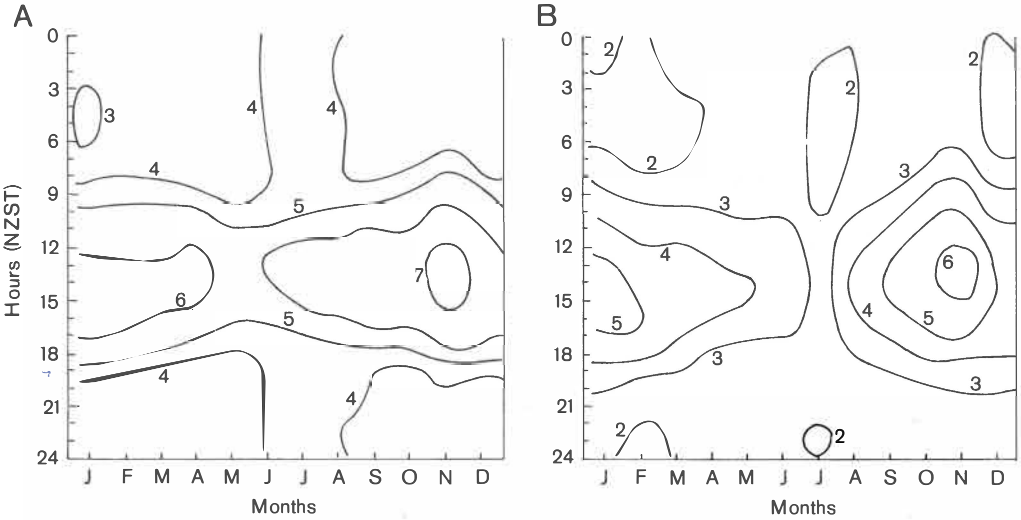


Fig. 3 Annual and diurnal variation of average surface wind speed (m s^{-1}; 1 m s^{-1} = 3.6 km hour) at (**A**) Kaitaia (North Island), 1962-69, (**B**) Dunedin Airport (Momona, Taieri Plain, South Island), 1963 – 68. Note the increase in speed in spring. Dunedin Airport is in a basin some way from the sea and shows an additional "continental" influence — low wind speed at night in winter compared with Kaitaia, (from Coulter 1973).

During the day wind speeds follow the curve of net radiation with maximum velocities between 13.00 and 15.00 hours and then dropping during the night by 1–3 $m.s^{-1}$. For most locations wind speeds are lowest during the winter months (June to August), with marked increases during spring and early summer. This seasonal pattern is rather different from that of several locations in the USA (Fig. 4) where except for coastal California, WEF is highest in winter and declines markedly in spring to low summer values. The coincidence of peak winds and the maximum seasonal increase in solar radiation is particularly significant for mixing in New Zealand lakes. Wind gustiness is also an important feature of New Zealand's climate which will tend to accentuate the effect of coincidence of high wind speeds with lake stratification. Instantaneous gusts of up to 240 km h^{-1} have been measured in the Southern Alps (Tomlinson 1975) and tropical cyclones may bring very strong winds and rain to northern New Zealand from late summer to early autumn. Wind gusts between 49 m s^{-1} (176 km h^{-1}) and 55 m s^{-1} (198 km h^{-1}) have been recorded during the passage of such cyclones (Maunder 1970).

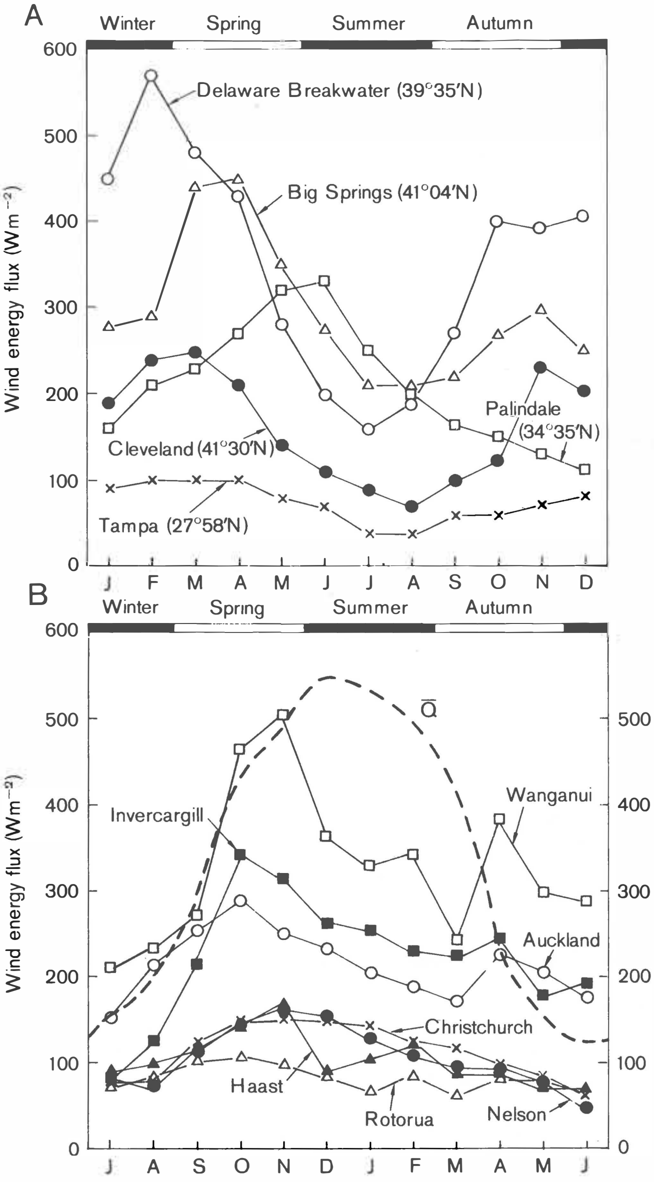


Fig. 4 Mean seasonal variation in mean wind energy flux (WEF) (proportional to wind velocity) in several (**A**) U.S. and (**B**) New Zealand locations with complementary latitudes (modified after Cherry 1976). Annual variation in average global radiation (Q) at Taita (Wellington, N.Z.) for the period December 1965 to June 1966; May 1967 to February 1968 are shown in (**B**) (after Coulter 1973).

GENERAL PATTERNS OF THERMAL STRATIFICATION AND MIXING

Because of mild winter temperatures caused by the oceanic climate all New Zealand lakes which develop thermal stratification are warm monomictic (= cheimomictic), as far as is known (Stout 1973; Jolly & Irwin 1975). A selection of typical seasonal profiles are shown in Fig. 5. Some degree of stratification usually lasts for 6 – 7 months, from October or November until April or May, followed by winter holomixis of 2.5 months or more.

Hutchinson & Löffler's (1956) analysis of the latitudinal and altitudinal distribution of

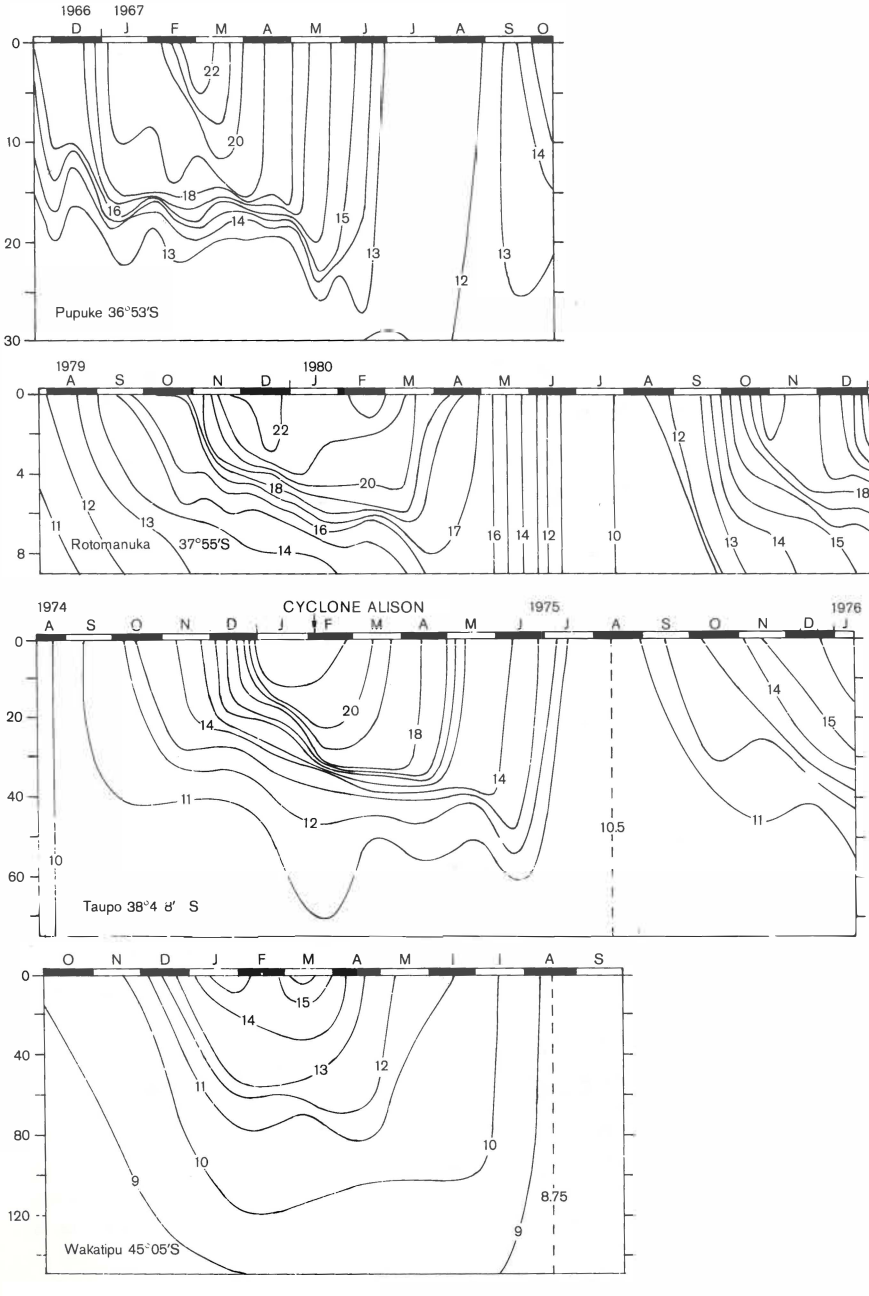
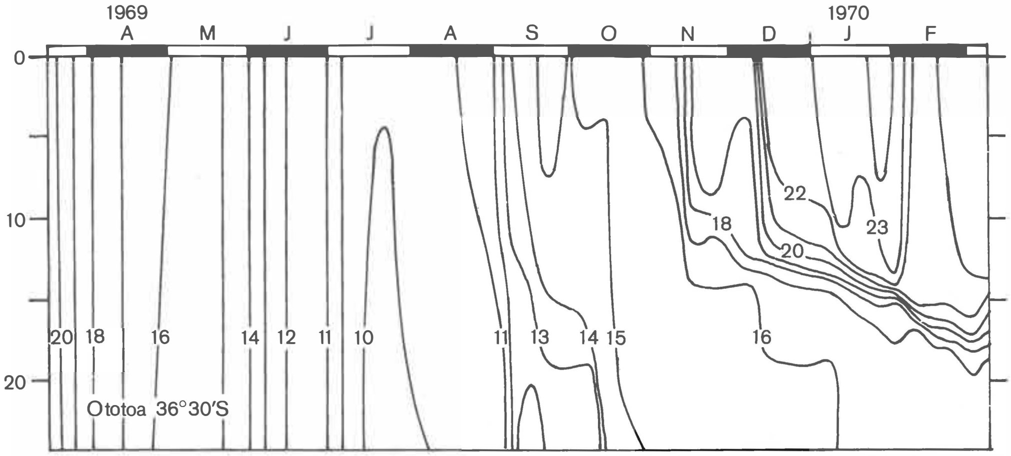


Fig. 5 Seasonal changes of temperature with depth in a selection of New Zealand lakes that develop summer thermal stratification. Isotherms are drawn at 1 °C intervals. Note that the depth scales differ and that they do not extend to the maximum depth in the cases of Pupuke (maximum depth = 55 m), Taupo (maximum depth = 163 m), Rotoiti (maximum depth = 33 m). The diagram for Wakatipu has been constructed from measurements made in different years. The effects of Cyclone Alison (Jan/Feb 1975) on Lake Taupo can be seen. Data sources: Barker (1970) Pupuke; Green (1975a) Maratoto and Ototoa; J.D. Green (original) Rotomanuka; Irwin & Jolly (1970) Wakatipu; V.H. Jolly (pers. comm.) Okaro; Mitchell & Burns (1979) Hayes; W.F. Vincent (pers. comm.) Rotoiti; A.B. Viner (original) Taupo. (Fig. 5 is continued overleaf.)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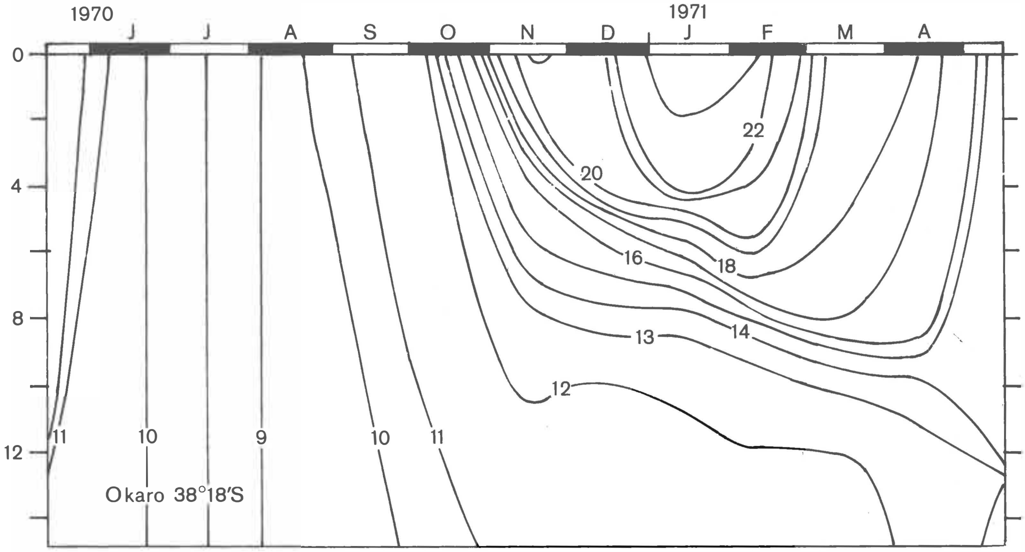
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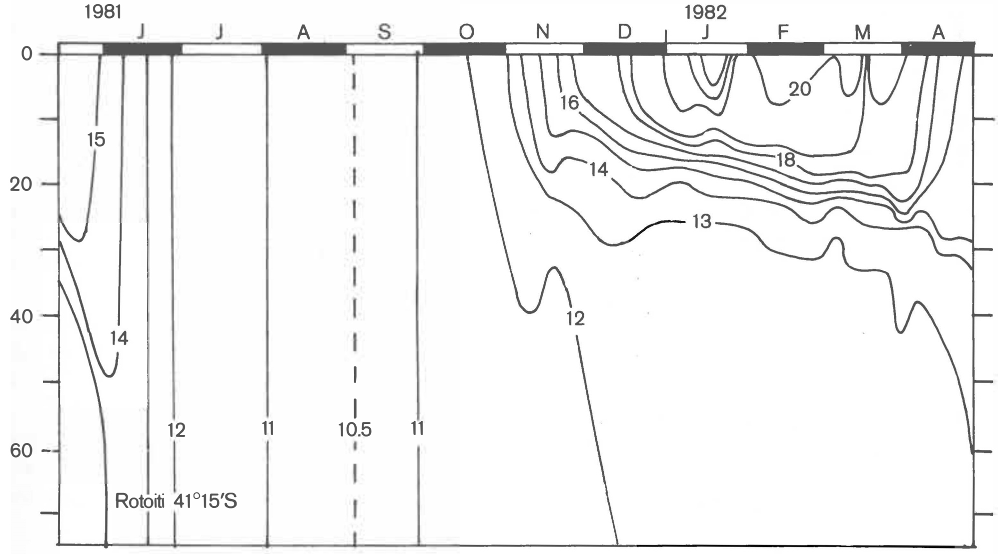
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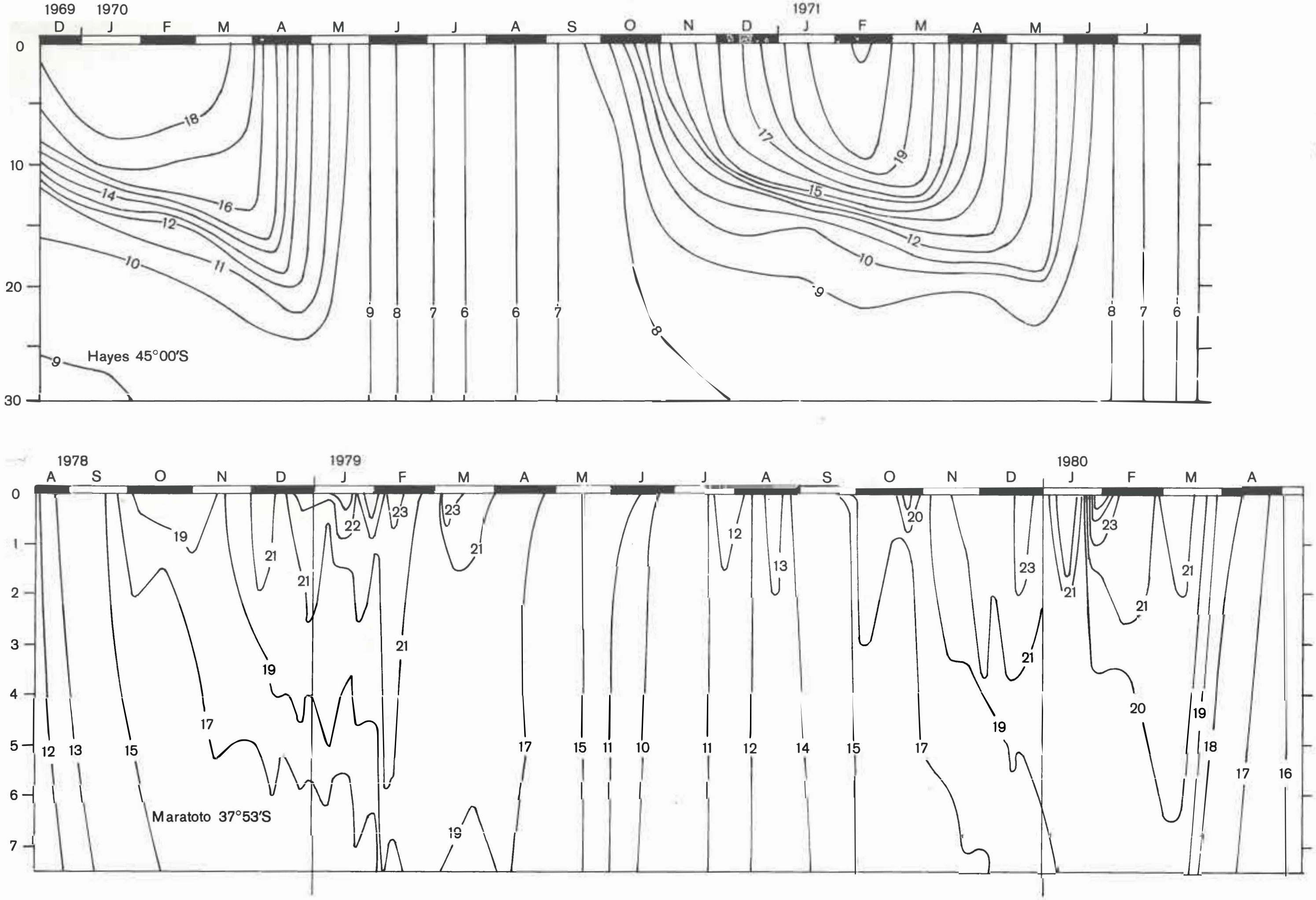


Fig. 5 Continued, (see previous page for caption)

lake thermal categories suggests that dimictic lakes should occur at altitudes above c.300 m in the South Island area where mean temperatures of the coldest month may fall below 4 °C. However, no dimictic lakes for New Zealand have yet been recorded in the literature. The nearest approach to them is found in small South Island ponds which freeze over in winter and develop transient thermal stratification in summer, e.g., Abbots Pond (Jamieson 1985). This apparent absence of true dimictic lakes may simply reflect a lack of observations on enough lakes, but even if such lakes are eventually found it seems certain that they will not be common, because of the combined effects of the oceanic climate and the size distribution of lakes in the South Island. Due to their glacial origins, high altitude South Island lakes tend to be either very large, occupying glacially deepened valleys, or relatively small kettles and tarns. The large lakes have such great thermal inertia that they never lose enough heat to freeze over in the few very cold winter days. On the other hand most of the smaller lakes are so shallow that even if they freeze over for a short period in winter, they never stratify in summer because of strong winds, the effects of which are often accentuated by the funnelling of wind by the mountainous terrain (Stout 1969, 1984). Such small monomictic South Island lakes with winter temperatures less than 4 °C, and which remain mixed during summer at temperatures well above 4 °C, do not fit into Hutchinson & Löffler's (1956) generally accepted thermal classification of lakes, which requires cold monomictic lakes never to exceed 4 °C and warm monomictic lakes always to exceed 4 °C. Bayly & Williams (1973) have suggested a suitable modification of the classification by subdividing the warm monomictic category into thereimictic (lakes such as the small South Island ones just described) and cheimomictic (equivalent to the normal warm monomictic category). This certainly provides a more accurate description of stratification patterns in New Zealand lakes. In addition, a number of medium sized lakes, particularly in northern New Zealand, e.g., Lake Rotorua (Fish 1975) and many of the small Waikato lakes (J.D. Green and M.A. Chapman, pers. comm.); Parkinson's Lake (Mitchell et al. 1984), are probably more properly defined as polymictic.

QUANTIFICATION OF THE POTENTIAL FOR LAKES TO MIX

Annual temperature data for 20 New Zealand lakes have been converted to the amount of work (kg m^2 s^{-2}) required to be done by wind at the lake surface to mix the lakes to isothermy against the density gradient, during the annual cycle of stratification (Viner 1984). This is the stability calculation of Schmidt (1928) and Birge (1916) as formulated by Idso (1973) (and converted to S.I. units). It was shown (Viner 1984) that the total amount of work that had to be done against the total stability during the year was linearly proportional to the theoretical maximum that would have to be done when a lake was at its maximum thermal stability in summer. Using this maximum stability as an index, the lakes could be related by a simple power equation which described maximum stability (and therefore seasonal stability) as a function of lake mean depth (Fig. 6). This relationship shows that the range of lakes in New Zealand encompasses sizes large enough for depth to cease having an effect on the annual flux of stability, that is, where temperature changes in the hypolimnion are not significant in the overall density changes. For comparing New Zealand lakes with those elsewhere the relationship also indicates the maximum stability possible under New Zealand's climatic conditions. Potentially, therefore, comparisons with parallel data for other lakes would illustrate, by the shape of the curve, the extent to which regional differences exist in the climatic distribution of kinetic energy along the water column.

The lakes listed in Table 2 illustrate this point. The two lakes in the Canadian Experimental Lakes Area (ELA) are fairly small. Although they are in a cool continental type climate and so experience much greater annual temperature changes than New Zealand waters, the amount of work required to mix summer startification (seasonal maximum stability) is not different

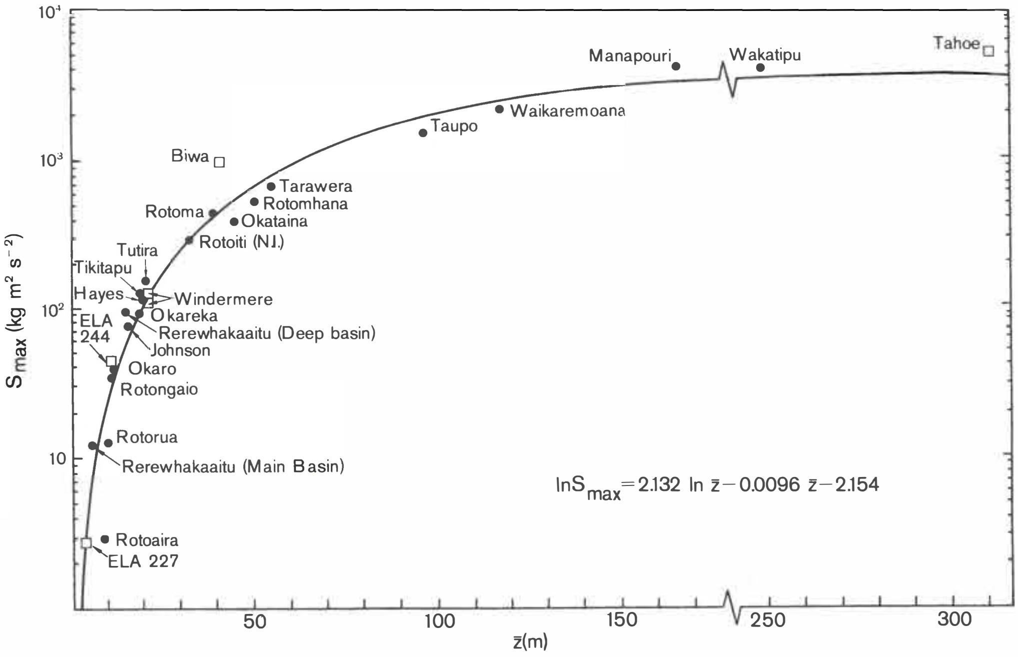


Fig. 6 Graph and equation to show the relationship of seasonal maximum stability (S_{max}) to mean depth (z). for New Zealand lakes. (from Viner 1984). Four lakes from other parts of the world are included (☐) for comparison.

from similarly deep lakes in New Zealand (Fig. 6). The moderate sized Windermere also fits exactly on the curve in Fig. 6, even though its climate is marine influenced and its summer air temperatures and lake surface temperatures are similar to those in New Zealand. The much cooler winter temperatures which are carried through to the summer hypolimnia do not make any significant difference to the seasonal maximum stability. The large Lake Biwa is similar in area to New Zealand's Lake Taupo, though less deep. Like the ELA lakes it has a "continental" climate (proximity to the Asian land mass) but its maximum stability is far greater by 2.4 times than it would be in New Zealand. The very large Lake Tahoe must be somewhat maritime influenced (270 km from the coast), though at high altitude. Its maximum stability is greater than anything possible for the largest New Zealand waters but only by 1.3 times (Fig. 6). The ratio between total stability through the summer stratified period and the summer maximum stability for New Zealand waters, is 150 (Viner 1984), but the lakes listed in Table 2 have significantly smaller values for this ratio. This suggests high seasonal maxima relative to total stability for the non-New Zealand lakes, which would conform to greater depths of mixed zones in New Zealand waters.

The conversion of temperature gradient data to stability gradients has also provided some information about comparative ecosystem functioning for New Zealand lakes (Viner 1984). Smaller lakes could be shown to have sharper gradients of stability along the upper parts of the water column than large lakes. Thus smaller lakes are inherently more likely to promote the growth of buoyant blue-green algae than larger ones. However, large lakes have most of the vertical change in stability located at the base of the epilimnion where metalimnetic peaks of phytoplankton might be encouraged (see also chapter 7).

SEASONAL TEMPERATURE RANGE

Seasonal maximum and minimum temperatures and the difference between the two (the seasonal temperature range = STR) are primarily dependent on the latitudinal shift in the cycle of solar radiation, altitude, the volume/area of the lake (i.e., the mean depth), the oceanic or continental, influence, and the scatter and absorption of light through the water (humidity, evaporation and shore protection can have some influence). The relative importance of these factors in New Zealand lakes is not well known. Jolly & Irwin (1975) give data from a small number of lakes showing a latitudinal effect of 0.4 °C per degree of latitude at all seasons in large lakes, with 0.3 °C °L^{-1} (summer) and 0.7 °C °L^{-1} (winter) for shallow lakes. They also quote a few examples of the effect of altitude on lake temperature ranging from 0.3 to 0.7 °C 100 m^{-1} , and noted that the effect could be greater in small lakes rather than in large ones. Irwin (1978) found that for Lakes Rotoroa and Rotoiti (South Island), which differ in altitude by 165 m, the temperature difference between them at all seasons was in accord with that expected on the basis of the average atmospheric temperature lapse rate (0.6 °C 100 m^{-1}).

Information on mean epilimnetic temperatures in New Zealand lakes is limited, but surface temperatures have often been measured and are used here as representative of mixed zone temperatures. This approximation is reasonable for large lakes, however, during the summer, surface temperatures may be less representative of mixed layer temperatures in small lakes. These often have no clear epilimnia but rather a temperature gradient, (which may be as much as 5 °C in New Zealand), from the surface to the seasonal thermocline. This is probably because small lakes have less fetch than larger ones, so that energy is transferred downward less readily. They are also often coloured or highly fertile and so more likely to have low light penetration than larger lakes, thus trapping incoming irradiation in the surface layers. Such effects could lead to the overestimation of maximum average mixed zone temperatures and thus also of STR.

It is possible to define the combined effects of mean depth, latitude and altitude on STR, and maximum and minimum temperatures by linear multiple regressions. For this, surface temperatures are available form 37 North Island and 27 South Island lakes (Table 5). The regression equations are listed in Table 4 which shows that STR is not significantly related to latitude or altitude because these factors act upon both maximum and minimum temperatures in similar ways. STR, maximum and minimum temperatures, are each strongly related to mean depth (see also Fig. 7) which is probably mainly due to the greater volume of water to be heated per unit area of lake surface in deeper lakes, although this result is likely to be partly caused by using only surface temperatures, (see above.)

Thus latitude affects maximum temperatures by 0.43 (± 0.07) °C °L^{-1} and minimum temperatures by 0.58 (± 0.05) °C °L^{-1} , while altitude affects maximum temperatures by 0.53 (± 0.1) °C 100 m^{-1} minimum temperatures by 0.54 (± 0.09) °C 100 m^{-1} , results that generally bear out the findings of Jolly & Irwin (1975).

Year to year variation in seasonal temperature range can be quite large and may contribute to the variance in the plots in Fig. 7. Maximum temperatures differ more than minimum temperatures from year to year. Thus in Lake Rotoiti (North Island), in seven years of observation, annual range varied from 8.7 °–12.7 °C, minimum temperature from 9.4 °–11.0 °C, and maximum temperatures from 19.3 °–23.2 °C; in Lake Taupo (4 years data), annual range varied from 6.4 °–12 °C, minima from 10 °–10.6 °C, and maxima from 16.9 °–22.0 °C, in Lake Hayes (3 years data) annual range varied from 12.75 °–15.3 °C, minima from 5.25 °–6.25 °C, and maxima from 18.5 °–21.1 °C.

Stout (1973) and Jolly & Irwin (1975) commented that the STR of New Zealand lakes is not as great as in lakes at similar latitudes elsewhere. In order to confirm this point we

Table 2 Selected overseas lakes to be compared for their stability with the New Zealand lakes in Fig. 7. (Appropriate values have been extracted or recalculated from the sources).

Lake	Lat.	Climate	Mean depth (m)	Maximum seasonal stability (kg m²s⁻²)	Total annual stability (kg m²s⁻²)	Total/ seasonal stability	Data Source
ELA 227	–	Continental	4.4	27.5	no data	–	Quay et al. (1980)
ELA 224	–	Continental	11.6	43.9	no data	–	Quay et al. (1980)
Windermere 1973	54° 20′N	Maritime	21.3	121	13.1×10^3	108	George (1981), Ramsbottom (1976) Jenkin (1942)
Windermere 1974	54° 20′N	Maritime	21.3	101	12.6×10^3	125	George (1981) Ramsbottom (1976) Jenkin (1942)
Biwa (mean 1969-74)	35° 15′N	Continental	41	1023	12.5×10^4	133	Mori (1980)
Tahoe 1971	39° 09′N	Maritime (alpine)	313	5430	2.45×10^6	111	Goldman (1974)

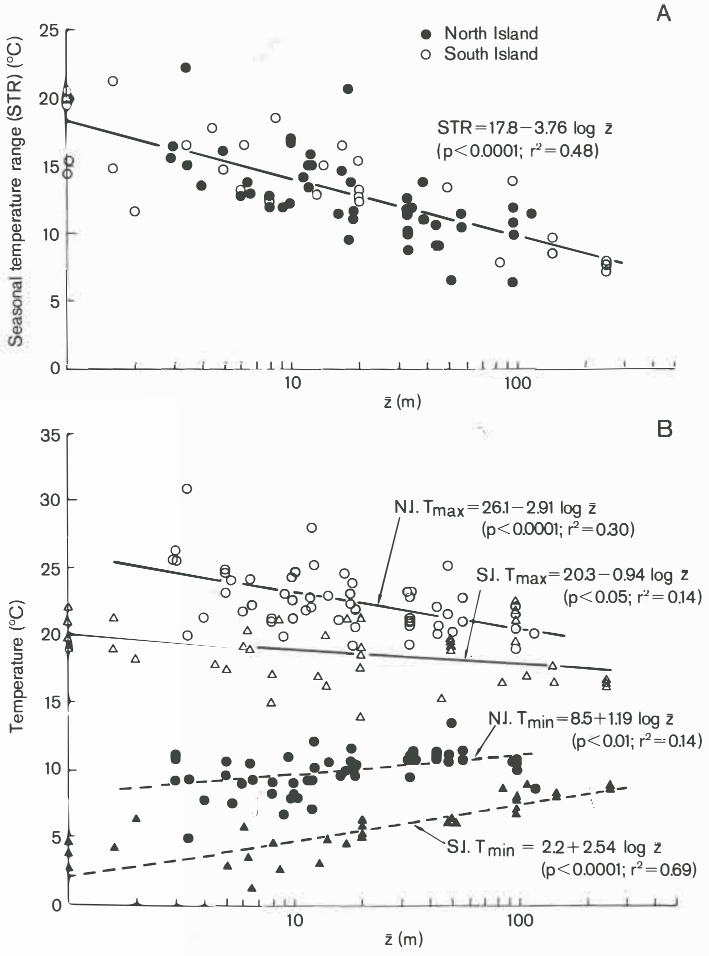


Fig. 7 Relationship between **(A)** annual temperature range (T.R. = $T_{max} - T_{min}$), and **(B)** between yearly maximum (T_{max}) and minimum (T_{min}) temperatures and mean depth (z) in North Island (N.I.) and South Island (S.I.) lakes. N.I.: T_{max} = open circles, T_{min} = solid circles. S.I.: T_{max} = open triangles, T_{min} = solid triangles.

Table 3 Thermal structure of New Zealand lakes

Lake Grouping	Total Number of Records	Stratified No.	Stratified %	Unstratified No.	Unstratified %	Reference
North Island coastal	30	7	23	23	77	Cunningham et al. 1953, Bayly 1962, Barker 1970, Green 1976.
Waikato	24	5	21	19	79	Original data
Rotorua/Taupo	17	13	77	4	23	Jolly (1968), Irwin (1968), McColl (1972)
Large glacial	9	7	78	2	22	Jolly (1968), Jolly & Irwin (1975)
Canterbury high country	15	0	0	15	100	Stout (1969)
Westland	8	5	63	3	37	Paerl et al. (1979)
Fiordland	7	7	100	0	0	Stout (1974)
Artificial	12	8	67	4	33	Jolly & Irwin (1975), Coulter et al. (1983)
Total	122	52	43	70	57	

have compared STR in New Zealand lakes with the data presented by Straskraba (1980) and Arai (1981).

Straskraba (1980) related the amplitude of variations in lake surface temperatures to the annual sinusoidal cycle of solar energy input as it varied with latitude, using the empirical polynomial equation:

$$T_s(\phi',t) = 28.1 - 0.34\phi' + (0.54 - 0.045\,\phi' + 0.014\phi'^2 - 1.97\times10^{-4}\times\phi'^3)\sin(t-\gamma_{1s})$$

where

$T_s(\phi, t)$ = surface temperature at day t of the year beginning January 1 for the given corrected latitude ϕ' (°C).

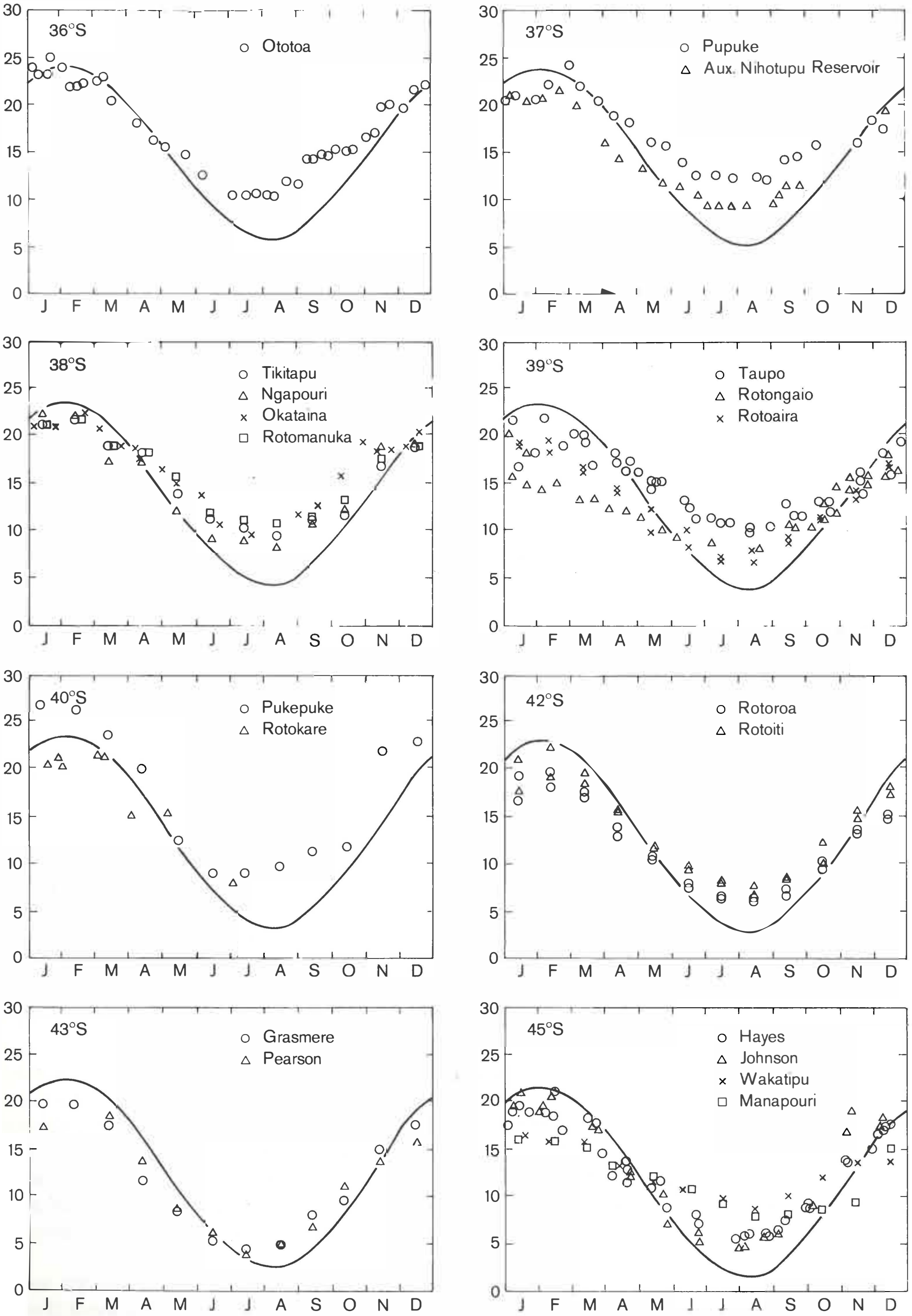
ϕ = geographical latitude corrected for the location of the meteorological equator at 3.4°N (degrees)

γ_{1s} = the phase angle for surface temperature (degrees). For the Northern Hemisphere $\gamma_{1s} = 240$; for the Southern Hemisphere $\gamma_{1s} = 60$.

The equation applies to an idealised medium sized lake, defined as having an area of 100 ha (i.e., average length c.1 km), maximum depth of 30 m, and conical shape. The model described the seasonal temperature range of various European lakes very precisely (cf. Fig. 3.16 in Straskraba 1980).

For New Zealand, the predicted annual cycle of surface temperatures, at representative latitudes, calculated from this equation are shown as solid lines in Fig. 8. They are compared with actual temperatures of lakes at these latitudes. Most of the lakes chosen approximate to the lake dimensions for which the equation was derived. It is clear that the surface temperatures of New Zealand lakes do not correspond well to the predicted curves. The New Zealand lakes have much warmer winter temperatures (c.5° higher) and many have cooler summer temperatures (often c.2° lower). The lakes with temperatures closest to the predictions are the small high country Canterbury lakes (Grasmere, Pearson) studied by Stout (1969), although their winter and summer temperatures are still significantly different. Larger New Zealand lakes (e.g., Okataina, Taupo, Wakatipu, and Manapouri) depart even further from the predicted values than the medium sized lakes. Thus New Zealand lakes show a much subdued annual temperature range when compared with the mainly Northern Hemisphere lakes on which Straskraba's equation was based.

Using a more theoretical approach, Arai (1981) predicted global values for the annual ranges of surface temperatures for lakes from the balance between nett radiation input (known


36°S
○ Ototoa
37°S
○ Pupuke
△ Aux. Nihotupu Reservoir
38°S
○ Tikitapu
△ Ngapouri
× Okataina
□ Rotomanuka
39°S
○ Taupo
△ Rotongaio
× Rotoaira
40°S
○ Pukepuke
△ Rotokare
42°S
○ Rotoroa
△ Rotoiti
43°S
○ Grasmere
△ Pearson
45°S
○ Hayes
△ Johnson
× Wakatipu
□ Manapouri
0
5
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for different latitudes) at the water surface, and theoretical sensible and latent heat transfers. A minimum range was predicted near the equator, a maximum in middle latitudes in the Northern Hemisphere, and rather lower values in the Southern Hemisphere, presumably because of oceanic influences (Fig. 9A). Actual annual ranges of surface temperatures of lakes are shown in Fig. 9B. Northern Hemisphere lakes fitted the predictions well, but there were few data for the Southern Hemisphere. Our additional data show that annual ranges for North Island lakes (mean; 13.0 ± 3.1 °C) and South Island lakes (mean; 14.0 ± 4.0 °C) fall close to the predictions for the Pacific region and South America. The mean values of North Island and South Island lakes are respectively 8.0 °C and 5.2 °C lower than those for lakes at equivalent latitudes in the Northern Hemisphere (Fig. 9B), differences which can be attributed to the ameliorating effects of New Zealand's oceanic climate. For example, in New Zealand lakes sensible heat losses will be reduced, particularly in the winter, because of relatively high winter air temperatures and low summer air temperatures, while evaporative heat losses will be relatively high in spring and summer due to the high wind speeds during these seasons.

This reduced seasonal temperature range for New Zealand lakes has a variety of probable consequences. The most marked differences from lakes in the Northern Hemisphere occur during the winter, when most New Zealand lakes have temperatures c.5 °C higher. This might encourage the winter primary production peaks often observed in New Zealand waters, although the main reason for these must be the enhanced mean light climate in the mixed water column (see chapter 7) since very high rates of primary production are known to occur over much greater temperature ranges in other regions. Workers on North Island calanoid copepods have suggested that lack of seasonal variation in temperature and food levels may lead to these animals being food limited for most of the year, and thus displaying low production:biomass ratios (see chapter 8). The extent of such effects elsewhere in the ecosystem are yet to be examined, but it can be reasonably assumed that high winter temperatures will transfer in summer to elevated hypolimnetic temperatures, and lead to low density differences between epilimnion and hypolimnion. This will act generally to increase the potential in New Zealand lakes for vertical mixing during the stratified period by requiring relatively less work to be done at the lake's surface for the same depth of mixing in temperate continental situations (see previous section).

DEPTHS AND GRADIENTS OF STRATIFICATION

In New Zealand the proportion of homothermal lakes is probably relatively high (Stout 1973b; Jolly & Irwin 1975); (Table 3), and many lakes which would stratify in Europe or North America do not do so here, where lakes of mean death of 10 m or less are likely to have little or no stability (Viner 1984). This is illustrated by comparing Clear Lake in California with New Zealand's Lake Rotorua. These lakes are in equivalent latitudes, have oceanic climates and dimensions approximately similar (mean depths: Rotorua, 11 m; Clear Lake, 10.5 m). Rotorua only occasionally stratifies, but Clear Lake has some stratification, though irregularly, through-

Fig. 8 *(Opposite)* Comparison of annual surface temperature variations of selected New Zealand lakes with predictions from Straskraba's (1980) equation (solid lines). The equation describes annual temperature variations in lakes as a function of variation in solar energy input and latitude (see text), and was developed for standard lake dimensions of area = 100 ha (i.e. length, L, = 1 km) and maximum depth (z) = 30 m. Most of the New Zealand lakes chosen have similar dimensions (Ototoa, L = 2.5, z = 28; Pupuke, L = 1.2, z = 55; Tikitapu, L = 1.6, z = 28; Ngapouri, L = 0.7, z = 24; Rotomanuka, L = 0.64, z = 9; Rotongaio, L = 1.1, z = 22; Rotoaira, L = 6.3, z = 14; Rotokare, L = 0.8, z = 11; Grasmere, L = 1.5, z = 15; Pearson, L = 3.7, z = 17; Hayes, L = 3.1, x = 33; Johnson, L = 0.9, z = 27), but others are larger or smaller (Aux = Nihotupu, L = 0.35, z = 9.5; Okataina, l = 6.2, z = 79; Taupo, L = 40.5, z = 163; Pukepuke, L = 0.7, z = 0.8; Rotoroa, L = 14.2, z = 145; Rotoiti, L = 8.2, z = 82; Wakatipu, L = 75.2, z = 380; Manapouri, L = 28.3, z = 444). Latitudes are approximate.

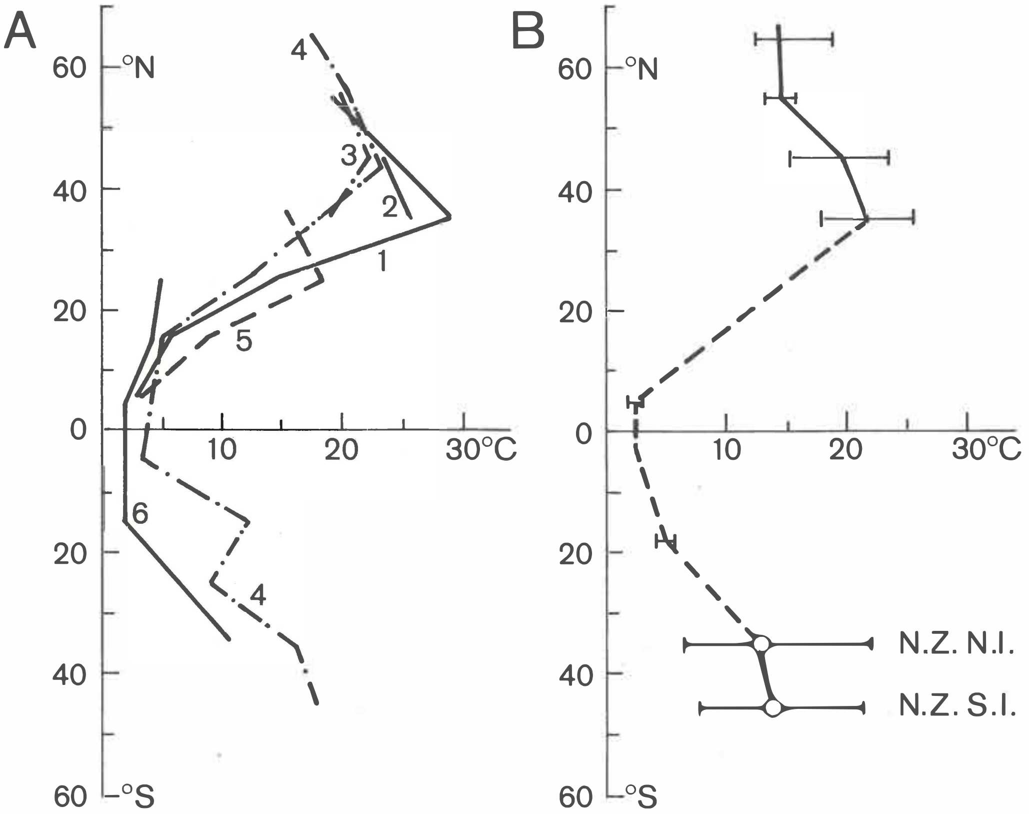

Fig. 9 The latitudinal distribution of the predicted annual range of equilibrium surface water temperatures in lakes (**A**), and the annual ranges of surface temperature actually observed (**B**). In (**A**) the predicted range has been calculated assuming that the annual minimum weather temperature is 0 °C. 1 East Asia, 2 Japan, 3 Europe, 4 North and South America, 5 West Asia and North Africa, 6 Pacific region including Australia, modified from Arai 1981, with the addition of data from New Zealand North Island (N.Z. N.I.) and South Island (N.Z. S.I.) lakes).

Table 4 Multiple regression equations explaining variations of epilimnetic seasonal temperature range (STR). Annual maximum temperature (HI) and annual minimum temperature (LO), in terms of mean depth ($\bar{z}$), latitude (L) and altitude (A). *** = highly significant, n.s. = not significant, (n = 64).

$STR = 10.08 - 33.47(\log \bar{z}) + 0.17(L) + 0.00061(A)$
Coefficients: *** n.s. n.s.
Equation: *** $r^2 = 0.34$

$HI = 41.94 - 1.51(\log \bar{z}) - 0.43(L) - 0.0053(A)$
Coefficients *** *** ***
Equation: *** $r^2 = 0.61$

$LO = 30.33 + 2.27(\log \bar{z}) - 0.58(L) - 0.0054(A)$

Coefficients: *** *** ***
Equation: *** $r^2 = 0.79$

---

out the warmer half of the year, even in the shallowest arm of the lake (mean depth 7.5 m) (Horne 1975). It follows that New Zealand lakes that do stratify have relatively deep mixed layers (Jolly & Irwin 1975). This can be shown by a comparison of the epilimnetic depth/lake length (z_{e1}/l) relationship of New Zealand lakes (Fig. 10) with those of various mid-latitude Northern Hemisphere lakes (Table 6). The mean epilimnetic depths of the New Zealand lakes are 25% to 90% deeper than in the other lakes. Only the large Scottish waters have comparable mixing depths, probably because, like the large South Island lakes, they occupy long, deep glacial basins and are subject to strong oceanic wind effects.

New Zealand lakes have relatively low gradients of temperature in the metalimnion (Fig. 11) indicating that shear production associated with seiches may be of general importance for generating turbulence, as suggested also by the deep epilimnia. Thus hypolimnetic entrainment rates are probably relatively high in New Zealand lakes. As yet, there is little published about these aspects for New Zealand lakes but there are some reports of seiche movements

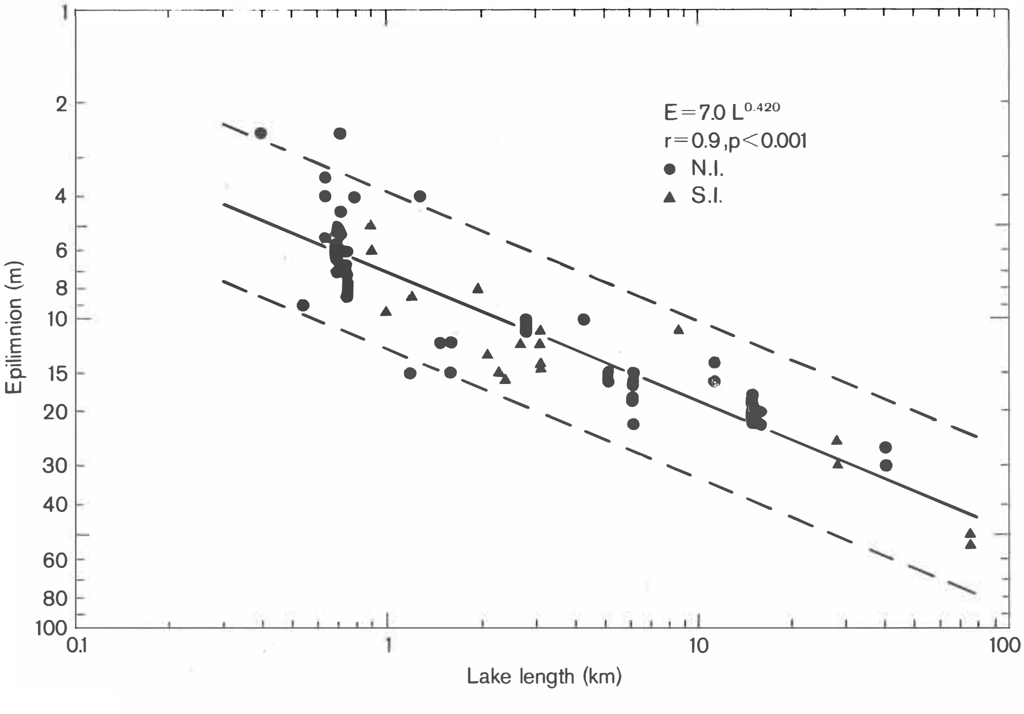

Fig. 10 The relationship between the midsummer depth of the epilimnion (E, m) and lake length (L, km) for New Zealand lakes. The dotted lines indicate the 95% confidence limits for individual measurements. For most of the lakes epilimnetic depth was defined after Welch (1948) as the upper layer of water with a temperature gradient of less than 1.0 °C m^{-1}. This definition could not be applied to Lakes Taupo, Wakatipu and Manapouri because even though they were stratified, the change of temperature with depth was so gradual that a gradient of 1 °C m^{-1} was never reached. In these cases, epilimnetic depth was measured at the point of bisection of the angle at the "knee" of the temperature curve. Where possible, measurements were made from profiles obtained in February or late January, the period of maximum temperatures and heat content in New Zealand lakes. Lakes included in this analysis (with number of records in parentheses) are: (N.I.) Aroarotamahine (1), Gin (1), Hamilton (1), Maratoto (1), Ngapouri (7), Okareka (3), Okaro (7), Okataina (5), Ototoa (1), Pupuke (1), Rerewhakaaitu (1), Rotoiti (6), Rotokakahi (1), Rotokare (1), Rotoma (2), Rotomahana (1), Rotomanuka (1), Tarawera (2), Taupo (2), Tikitapu (2), Waikaremoana (2); (S.I.) Ahaura (1), Eyles (1), Hayes (4), Johnson (2), Manapouri (2), Mike (1), Moke (1), Monk (1), Orbell (1), Te Au (1), Wakatipu (2).

Table 5 Mean annual temperature ranges for New Zealand lakes grouped by geographical area. n = number of annual records, * mean depths ($\bar{z}$) calculated from maximum depths (z max) using the relationship $\bar{z} = 0.532\ z_{max}^{0 \cdot 968}$ (n = 38, r = 0.98), calculated for New Zealand lakes by the authors.

Lake group	Approximate latitudinal range	$\bar{z}$ range (m)	Altitude range (m)	n	Mean annual range (°C)	Lowest record (°C)	Highest record (°C)	Source
Northland & Auckland coastal lakes	36° – 38°S	11 – 30*	3 – 64	3	14.3	10.2	27.9	Bayly 1962, Barker 1970, Green 1975
Auckland reservoirs	37°S	<10	20 – 283	4	13.0	7.9	24.2	Green 1974, Jolly & Irwin 1975
		11 – 30	215	1				
Waikato lakes	38°S	2.9 – 5	30 – 57	6	16.0	9.2	31.5	Original data
Waikato impoundments	38°S	<10*	341	1	12.8	11.9	24.7	Magadza 1973
		11 – 30*	54 – 229	2	11.7	10.7	23.0	
Rotorua/Taupo lakes	38° – 39°S	<10	293 – 438	5	13.3	7.8	24.5	
		11 – 30	352 – 438	8	13.6	9.3	23.9	
		>30	278-585	19	10.7	8.5	25.0	
Wanganui coastal lakes	40°S	<10*	0 – ?	4	17.2	7.0	29.0	Gibbs 1973, Taranaki Catchment Commission 1980)
Nelson glacial lakes	41°S	>30	444 – 609	8	13.6	6.0	22.5	Irwin (1978)
Canterbury high country lakes	42° – 43°S	<10*	600	13	15.9	0	21.3	Stout (1969)
		11 – 30*	600	2	15.2	3.2	21.0	
Southern glacial lakes	45°S	11 – 30	330 – 521	5	14.1	4.5	21.1	Mitchell & Burns (1979), Jolly (1959)
		>30						
Dunedin	46°S	<10	0 – 391	3	19.1	2.5	23.5	Mitchell (1971)

which indicate major sources of turbulent energy. Surface seiches are known from Lake Coleridge (Bottomley 1955) and Lake Wanaka (Cox 1965), but most information for South Island lakes comes from Lake Wakatipu. Here surface seiches with amplitudes between 2 and 8 cm have been studied by Bottomly (1955, 1956a, b), Cox (1965) and Heath (1975). The surface oscillation is a complex one in this dog-leg shaped lake as the three separate arms may oscillate independently and reinforce certain of the oscillations of the entire lake. Bottomley and Cox both found that the first two modes of 52 and 27 minutes predominated, but also recorded short term fluctuations, with periods between 2 and 5 minutes which were attributed to transverse oscillations. Heath (1965) applied spectral analysis to the variation in lake level and found at least 5 modes of oscillation with periods of 52, 26.7, 18.5, 15 and 10 minutes, which corresponded to theoretical predictions for the first 5 modes of oscillation over the entire length of the lake. Most energy was in the second mode (26.7 min) rather than in the fundamental mode (52 min). Heath showed that this was because the fundamental modes of the north and south arms of the lake (24.5 and 24.8 minutes respectively) were similar to the second mode for the entire lake, so that energy supplied to either of these two arms would tend to generate or reinforce the full lake second mode. Bottomley (1955) also observed surface oscillations with a period of c.12 hours which he attributed to the effects of an internal seiche. There have been no direct studies of internal seiches in this lake, but Irwin & Jolly (1970) found considerable thermocline slopes, with the epilimnion deepening towards the southern end of the lake by about 50 m. Heath (1975), using Irwin & Jolly's temperature data, calculated that the 12 hour surface oscillation noted by Bottomley may have been produced by the second mode of an internal seiche with an amplitude of c.10 m at the south end of the lake. The calculated period of the first and second modes for internal seiches of the entire lake were 155 and 78 hours respectively for January 1953.

In Lake Tekapo, Ridgway (1974) observed short-term periodic fluctuations in isotherms above and below the thermocline, with a period of 12.7 min., that were thought to be due to a surface seiche operating in the southern end of the lake. Differences in thermocline depth on successive days were also found, which indicated the presence of an internal seiche. The vertical displacement over approximately half a wave period was c.7 m, and the period was calculated to be c.48 hours. The most complete records of an internal seiche are those of Green et al. (1968) from Lake Rotoiti (N.I.). The amplitude was c. 8 m and the observed period 19.6 hours which agrees fairly well with the period of 21.2 hours to be expected from the lake's morphology. The oscillation was heavily damped and the thickness of the metalimnion varied markedly during the cycle. Fish (1975) found clear thermocline slopes attributable to seiche effects on 18 occasions during a 3 year study of this lake. The consequences of the high turbulence presumably associated with these seiches have yet to be adequately studied.

Because of their deep epilimnia, the ratio of area of sediment overlain by the epilimnion to the volume of the epilimnion will be greater in New Zealand lakes than in similarly sized Northern Hemisphere lakes. Fee (1979) has shown that a strong positive correlation exists between this ratio and rates of primary production in Canadian Experimental Lakes Area lakes possibly due to effects on rates of nutrient regeneration. This principle may operate in New Zealand to enhance nutrient supply for primary production, but probably just as important are the effects of the light climate throughout the mixed zone (see chapter 7).

For this aspect of material transfer the relatively weak metalimnetic temperature gradients would seem to be an important distinguishing influence in New Zealand lakes because of the implied enhanced eddy diffusion. Average metalimnetic eddy diffusion coefficients (A_{ML}) are estimated here for a number of New Zealand lakes using seasonal temperature profiles and the periodic temperature wave method (Dutton & Bryson 1962; Lerman & Stiller 1969). The relationship between A_{ML} and mean depth for New Zealand lakes is not significantly different from that for 14 northern temperate lakes calculated by Straskraba (1980) using the same

Table 6 Relationship between summer epilimnetic depth z_{EL} in m, L in km.

Author	Region	Regression $z_{EL} =$	r	Max L (km)	Number of lakes	z_{EL} (NZ)/z_{EL} L = 1	L = 5	L = 10
Patalas (1960, 1961)	Poland Baltic Lowland (54 °N)	$3.79L^{0.455}$	0.94	6.5	53	1.85	1.75	–
Arai (1964)	Japan (35 ° – 45 °N)	$5.46L^{0.33}$	–	12	32	1.28	1.48	1.58
D.W. Schindler quoted in Straskraba (1980)	Canadian Shield Lakes (42 ° – 51 °N)	$4.98L^{0.38}$	0.85	7	67	1.41	1.50	–
Yoshimura (1936)	Japan (32 ° – 50 °N)	$3.56L^{0.46}$	0.69	36	19	1.97	1.85	1.79
Ventz (1973)	E. Germany Baltic Lowland (c.53°N)	$4.04L^{0.39}$	–	7.5	30	1.73	1.82	–
I.R. Smith quoted in Straskraba (1980)	Scottish highlands (c.57 °N)	$4.66L^{0.55}$	0.64	28	59	1.50	1.22	1.11
	New Zealand[2] (36 ° – 46 °S)	$7.00L^{0.42}$	0.89	75.2	33[1]			

[1] z_{EL} determined on several occasions in some lakes so that n = 70.

[2] Data from Jolly (1959); Bayly (1962); Irwin (1968); Fish (1969), (1970); Baker (1970); Irwin & Jolly (1970); Irwin (1971); Stout (1974); Green (1975); Mitchell & Burns (1979); Paerl et al. (1979); Taranaki Catchment Commission (1980); Chapman et al. (1981); Vincent (1983); original.

technique, (Fig. 12). Although the method of calculation is rather crude and only gives an average seasonal estimate of diffusion rates the exercise does suggest that the seasonal mean is a less important mixing indicator in New Zealand than the vertical exchanges likely to occur over brief periods during storm events. These would be strong enough to generate considerable shear at the thermocline and substantially deepen the mixed layer, even in large lakes (e.g., the effect of Cyclone Alison on Lake Taupo, Fig. 5). Such effects in smaller lakes can be pronounced (e.g., Lake Rotongaio (Viner & Kemp 1983)). Mitchell & Burns (1979) calculated rates of diffusion of oxygen across the metalimnia of Lakes Hayes and Johnson from eddy conductivity heat transfers between epilimnion and hypolimnion, although the actual eddy diffusion coefficients were not given. They stated that eddy diffusion played only a small part in annual epilimnetic oxygen budgets, averaging 7% and 3% of photosynthesis in Lakes Hayes and Johnson, respectively. More important limnologically, eddy diffusion was estimated to contribute about 20% of the hypolimnetic oxygen consumption.

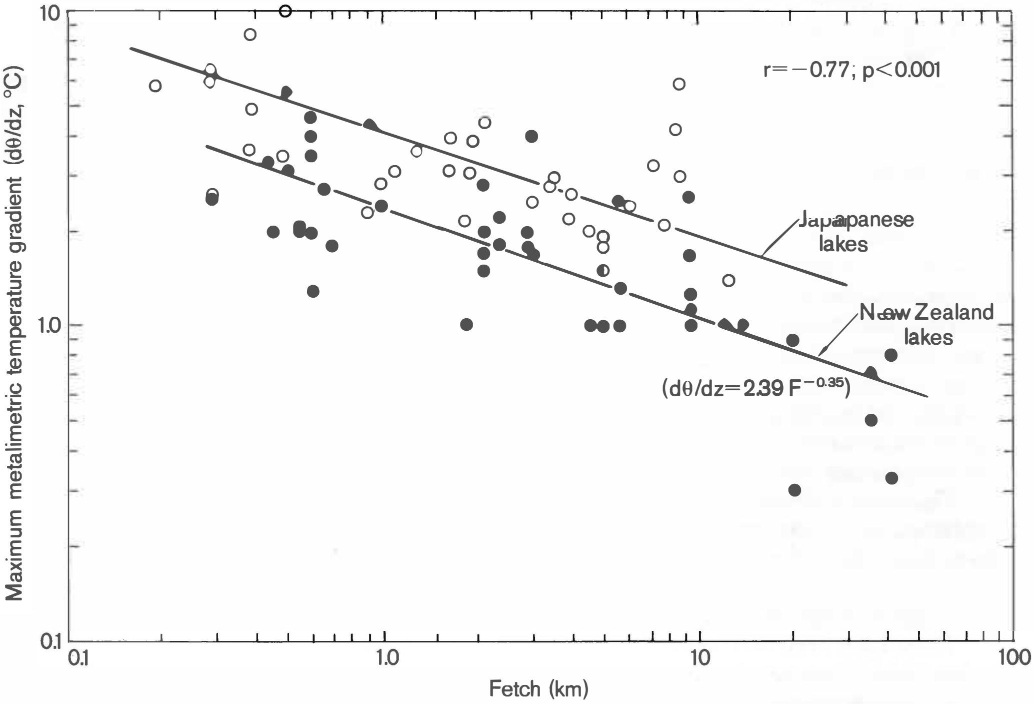

Fig. 11 Comparison of the relationship between maximum temperature gradient ($d\theta/dz$, °C) in the metalimnion and mean fetch (F, m) in New Zealand and Japanese lakes. The data for Japanese lakes are from Arai (1981).

A potential influence on the thermal and mixing regimes of New Zealand lakes is the input of geothermally heated water. However few instances of such effects have been investigated, the study of Lake Rotoiti (N.I.) (Priscu et al. 1986) being the exception and is the most detailed application of eddy diffusion estimation (by the method of Jassby & Powell (1975)) under New Zealand conditions. In this lake heated sediments (up to 130 °C) have been found in the deepest regions and so the lake is unusual in that heat transfer is not only downwards but also upwards. It was found that the geothermal energy source is small, 10–20 MW, compared with the incident solar flux at the lake surface, 2500–9200 MW. The geothermal input is even smaller compared with the flux of 100–400 MW across the thermocline. However this small, localised heat generates convectional mixing within the hypolimnion, so enhancing downward diffusion of the epilimnetic solar source energy through the thermocline. This convectional mixing was suggested to be particularly important in sustaining mixing in spring before the onset of strong thermal stratification, thus having marked repercussions upon the lake's productivity cycle. A numerical model was constructed which attempted to differentiate the diffusion effects on nutrients, chlorophyll, particulate nitrogen and phosphorus in the water column from the effects of metabolism on these components.

In Lake Rotomahana, Jolly (1968) found that epilimnetic temperatures were about 4 – 5 °C higher than in neighbouring Lake Tarawera, less than 1 km away and of smaller depth and volume. During winter also, temperatures of Rotomahana were about 4 °C higher. She suggested that heat might be supplied by various subterranean geothermal sources since hot springs around the shores of the lake were not considered to provide enough heat. McColl & Forsyth (1973) investigated the temperature structure of a highly thermal lake, Lake Rotowhero, in which temperatures varied seasonally from 29.75 °C– 37.5 °C, and which showed a difference of 1 °C between surface and bottom (5 m). Other small lakes in the nearby Waiotapu and Waimangu thermal areas also maintain elevated temperatures throughout the year due to geothermal influences (Lloyd 1959; Cross 1963; Healy 1975; Keam 1980).

SYNTHESIS

Lakes in New Zealand are all warm monomictic type. Only a few small lakes are known to freeze over in winter, but these are too shallow to stratify in summer. If treated as a group, as done here, the lakes can be distinguished from lakes in similar latitudes elsewhere by their reduced annual temperature range, enlarged depth of epilimnia and increased potential to mix. These features can be attributed to the influence of the surrounding ocean which limits the summer temperature rise and, more importantly, the winter drop in temperature, and which provides continually strong winds. Within this lake group, however, there is much variation in physical characteristics because of the large diversity of terrain, particularly altitude, and lake morphology (see also chapter 1).

This comparatively greater degree of mixing and mild winter temperatures must be reflected in enhanced mineralisation processes, enlarged zone of planktonic nett production during stratification and sustained ecosystem production through winter. Because shifts in mixed depth due to transitory weather conditions can occur relatively easily, short-term biological repercussions can be observed. These biological implications are discussed in chapters 7 and 8.

There have been no models published yet which attempt to predict mixing events in New Zealand lakes from weather conditions, so it is not possible to analyse the relative importance of wind and temperature upon the mixing process. Nevertheless, the apparently somewhat disconnected data for stability, epilimnetic depth, metalimnetic gradient and wind speed compiled here can be integrated by using the Wedderburn number (W), a dimensionless index which has been used for predicting the general pattern of wind induced water movements in stratified lakes (Spigel & Imberger 1980; Thompson & Imberger 1980; Imberger 1985b; Monismith 1985).

The Wedderburn number can be related to the lake stability discussed above by approximating the density stratification in a lake as a two-layer stratification with a density difference $\Delta\varrho$ between the two layers, and taking the depth, h, of the upper layer to be the depth of the wind mixed layer. If H is the total depth of the lake, the stability (potential energy required, per unit area, to mix the lake to isothermy) can be given by $\Delta\varrho\, gh(H-h)/2$, which is of the order $\Delta\varrho\, gh^2/2$ if h is of the same order as H. If the wind applies a stress τ on the lake surface, giving rise to a velocity scale $u_* = (\tau/\varrho)^{1/2}$ where $\varrho =$ the density of water, then the kinetic energy per unit area associated with water motions of order u_* in the mixed layer will scale with $\varrho u_*^2 h/2$. The ratio of potential energy (stability) to kinetic energy (associated with u_*) is then

$$\frac{\Delta\varrho g h^2}{2} \Big/ \frac{\varrho u_*^2 h}{2} = g'h/u_*^2 = \mathrm{Ri},$$

where $g' = \Delta\ \ g/p$ is the acceleration of gravity reduced by buoyancy effects, and Ri is a dimensionless variable known as the Richardson number. Expressed in this way Ri gives an integrated or overall measure for the mixed layer of the ratio of stability to kinetic energy. Note that when expressed in this form Ri is referred to as a bulk or overall Richardson number, as opposed to a gradient Richardson number which applies to local properties at a point in the water column (Turner 1973; pp.12 and 323). For a small to medium-sized lake, where Coriolis effects are unimportant, the length of the lake relative to the mixed layer depth is also a crucial parameter in determining the amount of kinetic energy actually available for mixing during a given wind episode (Spigel & Imberger 1980). This is allowed for in the Wedderburn number which combines the effects of stability, wind, and mixed layer aspect ratio in a single parameter (Thompson & Imberger 1980):

$$W = \mathrm{Ri}\frac{h}{l} = \frac{gh}{u_*^2} \bullet \frac{h}{l}$$

where l may be taken as the length of the lake at thermocline level in the direction of the wind. Methods for calculating W when the stratification is not strictly two-layered are discussed by Patterson et al. (1984).

At high values of W (weak winds, marked density stratification and/or a deep mixed layer), turbulence produced by shear at the base of the mixed layer is not an important source of mixing, and surface stirring by wave action, Langmuir circulation and downward convectional movement of cooled surface water are probably the most important processes producing turbulence. Consequently, little, or only very slow (Fischer et al. 1979) deepening of the mixed layer occurs. At W less than 1 (stronger average wind strengths and/or wind gusts, weaker stratification, and/or a shallower mixed layer), tilting and seiching of the thermocline occurs, which may be great enough to result in upwelling of metalimnetic water upwind, and also horizontal currents in the mixed layer. Shear associated with such currents may produce enough turbulent kinetic energy to cause hypolimnetic entrainment and rapid deepening of the mixed layer. When W is much less than 1, upwind upwelling on the upwind side of the lake is severe and metalimnetic water is mixed laterally across the lake. When wind stress subsides this upwelling water adjusts to its density level and intrudes into the thermocline, thickening the metalimnion.

It will be evident how our collected data for New Zealand lakes is relevant to this concept, but its utility can be illustrated further by reference to some representative waters. In Fig. 13 are seasonal changes in Wedderburn numbers for two contrastingly sized lakes; Taupo and the nearby Rotongaio. Taupo is also compared with the similar sized Japanese Lake Biwa which has a very different climate (see above). For all the lakes, high W values are established quickly during the annual cycle, and so surface stirring and convectional movements are probably the dominant mixing patterns for most of the stratified period. This appears to be typical for other types of lakes too, e.g., the South African Lake Le Roux (Allanson & Jackson 1983) and Hartbeespoort Dam (CSIR 1985). The Wedderburn number increase for Taupo is markedly delayed compared with Biwa. This is an important difference since it means that turbulence is likely to be generated at the developing thermocline for a more extended period in Taupo, with concomitant more efficient mixing. (This delay is not shown by stability calculations alone which yield very similar periods for stratification/destratification

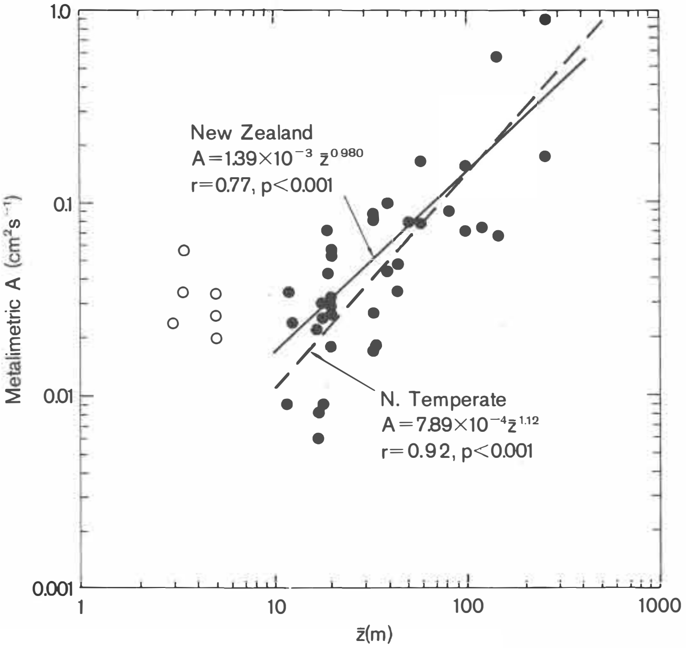

Fig. 12 Comparison of the relationships between coefficient of eddy diffusion (A) in the region of the metalimnion and mean depth (z) in New Zealand (dots) and Northern temperate lakes. A calculated by the periodic temperature wave method (Dutton & Bryson 1962, Lerman & Stiller 1969). The relationship for northern temperate lakes is that calculated by Straskraba (1980). Values from small Waikato lakes which have been omitted from the calculated regression for New Zealand lakes are shown as open circles.

in the two lakes.) Some caution is required in this comparison because both Taupo and Biwa are so large that the turbulence created by Coriolis effects could be significant enough to compromise the assumptions underlying the Wedderburn classification scheme (Spigel & Imberger 1980).

The Rotongaio Wedderburn numbers increase and decrease seasonally much more abruptly than for the two large lakes, as might be expected for the less inertia of the smaller water mass. This presumably also contributes to the reason for the considerable short-term variations in W. Also, there are two, rather than one, main peaks. Both the reduction of W in Rotongaio between October and December, and the delay of its increase in Lake Taupo during the same time coincide with the peak wind velocity during the year (Fig. 13, also Fig. 5). This timing of seasonal wind velocity has already been discussed above as unusual with regard to limnology. However, even the minor peaks in wind speed appear to correspond with the subsidiary peaks in W for Rotongaio. This close link with wind shows that the wind stress term (u_*^2) in the calculation of W is of greater importance for the smaller lake, and presumably others like it, than for the larger ones.

There is clearly a problem in using mean wind values for the calculation of W, since short gusts of wind could well be sufficiently long to cause major mixing events, and for the temperature profiles to represent the nett outcome of these gusts rather than the means over days. In Lake Rotongaio, even at high W values, and so only small turbulence at the thermocline, short term water column disturbances can have major effects on the plankton, and this lake is probably typical of smaller water bodies in which the nutrient environments of the epi- and hypolimnia are frequently highly contrasted, and where surface convectional water movement can be very important, even diurnally.

Although it is conceivable that in larger New Zealand lakes, such as Taupo, the rather weak temperature gradients at the thermocline are records of the high turbulence at the early stages of stratification rather than more immediate conditions, the data available from other

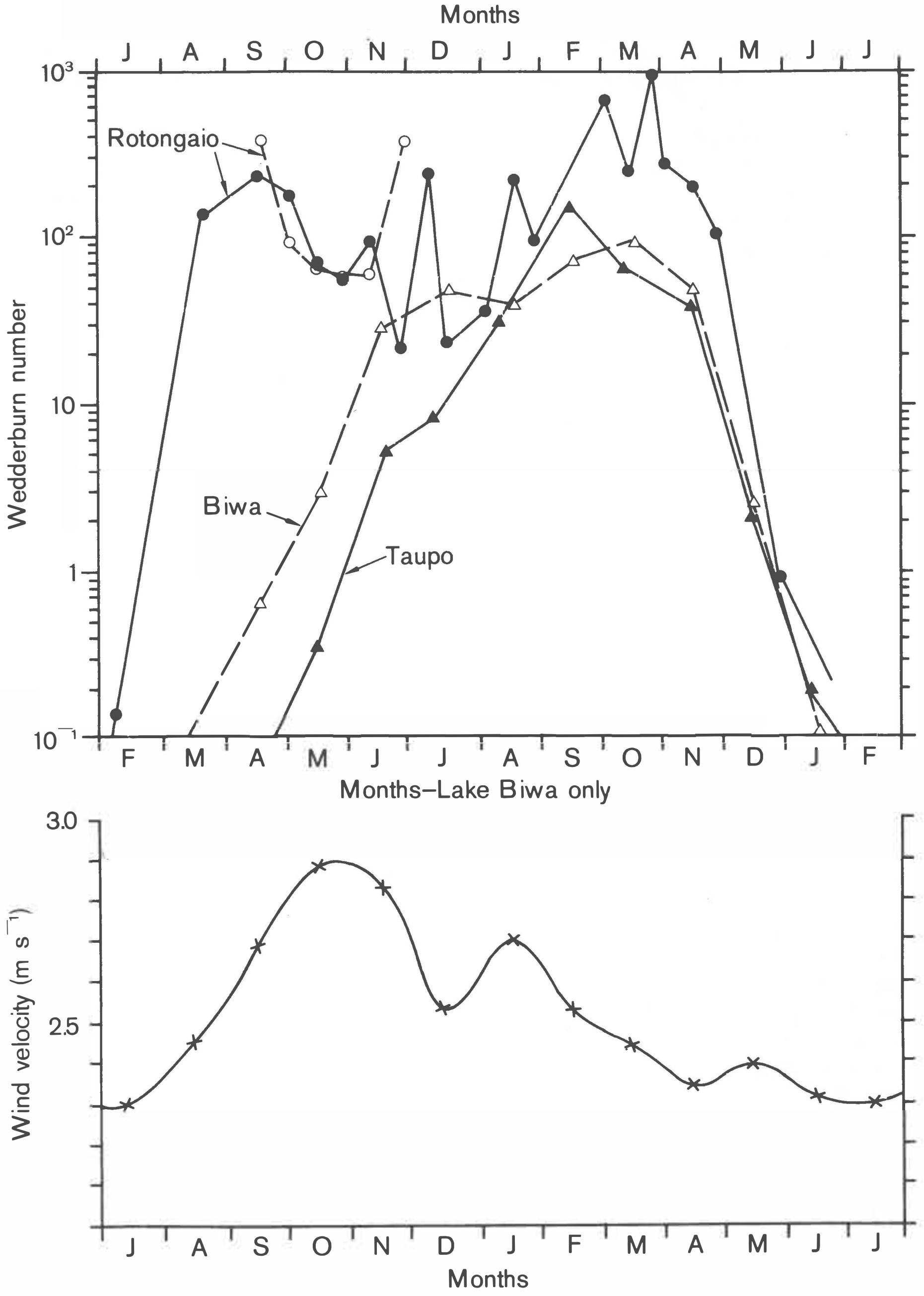

Fig. 13 Comparison of changing Wedderburn numbers (W) through the year for two New Zealand lakes; Taupo and Rotongaio, and Lake Biwa, Japan. The temperature data used in calculating W for Taupo is from 1974 – 75 (original), and for Rotongaio, 1979 – 80 (original) (the period September – November is duplicated). Mean wind speeds for Taupo and Rotongaio, also used for W and figured, are for 1949 – 70 and 1979 – 80 (N.Z. Meteorological Service 1970, and original). Temperature for Lake Biwa are means for 1967 – 72, and mean winds are for 1896 – 1970 (Mori 1980). The Northern and Southern Hemisphere seasons for Lakes Taupo and Biwa have been superimposed by aligning the months of maximum stability.

lakes for the calculation of Wedderburn numbers are too limited to allow for further light to be shed on mechanisms causing the distinctive density profiles in New Zealand lakes usually. Existing temperature information is generally unsuitable because it is normally too widely spaced and without accompanying weather data. The current information has been employed here, probably to its maximum utility, for broadly characterising New Zealand waters with respect to oceanic weather conditions, but the quantification of the relationship between mixing and the prevailing climate will have to rely upon the new generation of automated data collection suitable for numerical modelling. The necessity for this approach is further shown by the accumulating evidence (cf. references in Viner 1985) of the importance of the diurnally mixed (convectional) layer of water in the ecology of lakes. No proper fine scale study of this aspect of lake mixing has been carried out in New Zealand yet, but is an inevitable requirement for many applied limnological problems (chapter 7). Nevertheless, even without technological sophistication, our analysis suggests that it would probably be fruitful for ecological purposes to collect even basic temperature and weather data in a way suitable for calculating Wedderburn numbers and to pursue in greater detail the effect of wind on lake mixing at the early stages of stratification, and also to determine the gust period which is long enough to have an effect on the density profile.

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